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The lepton asymmetry: the last chance for a critical-density cosmology?

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ABSTRACT

We use a wide range of observations to constrain cosmological models possessing a significant asymmetry in the lepton sector, which offer perhaps the best chance of reconciling a critical-density Universe with current observations. The simplest case, with massless neutrinos, fails to fit many experimental data and does not lead to an acceptable model. If the neutrinos have mass of order 1 eV (which is favoured by some neutrino observations), then models can be implemented which prove a good fit to the microwave anisotropies and large-scale structure data. However, taking into account the latest microwave anisotropy results, especially those from BOOMERANG, we show that the model can no longer accommodate the observed baryon fraction in clusters. Together with the observed acceleration of the present Universe, this puts considerable pressure on such critical-density models.

Key words: cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

The recent use of the magnitude–redshift relation of type Ia supernovae to infer that the present Universe is accelerating (Perlmutter et al. 1998, 1999; Schmidt et al. 1998; Riess et al. 1999) has led to a consensus that the cosmological model best-fitting the current data is a spatially flat cold dark matter (CDM) Universe with a matter density around 0.3 of the critical density (Peebles 1984; Turner, Steigman & Krauss 1984; Efstathiou, Sutherland & Maddox 1990). This model, known as Λ CDM, can boast of an impressive range of observational successes, with its main drawback being theoretical objection both to the magnitude and to the required recent dominance of the cosmological constant term.

It is often stated that while the supernova results are powerful in themselves, it is unlikely that they would have been widely accepted had there not been a considerable amount of other evidence pointing towards this favoured cosmology (Krauss & Turner 1995; Ostriker & Steinhardt 1995). Amongst that, one might mention the shape of the galaxy correlation function, the combination of the cluster baryon fraction with standard big bang nucleosynthesis (BBN), and the flat geometry inferred from the cosmic microwave background (CMB) combined with the low matter density implied by direct observations.

In this paper, we examine the extent to which these additional arguments might be undermined in an alternative cosmological model, which features an asymmetry in the lepton sector leading to a higher than usual abundance of neutrinos. It was recently claimed (Adams & Sarkar 1998; Lesgourgues & Peloso 2000) that these

models offer one of the best remaining prospects for salvaging the idea of a critical-density Universe [the other main option being the Broken Scale Invariance models (Barriga et al. 2000)], and although the likelihood of doing so is small it is judicious to be aware of the possibility in order to balance its drawbacks with those of the cosmological constant model.

The lepton asymmetry model relies on primordial processes to create an imbalance between the numbers of neutrinos and antineutrinos in the Universe, which may reside in any of the three neutrino families. This would be the leptonic analogue of the (presently unknown) processes leading to the baryon number of the Universe, although in this case interesting effects only arise for an asymmetry of order 1, whereas the baryon-to-photon ratio is of order 10^{-9} . There are many particle physics motivated scenarios for generating such a large lepton asymmetry (e.g. Foot, Thomson & Volkas 1996; Casas, Cheng & Gelmini 1999; March-Russell, Murayama & Riotto 1999; Dolgov et al. 2000; Kirilova & Chizhov 2000; McDonald 2000; Di Bari & Foot 2001). The lepton asymmetry leads to two important physical effects. The first is that it modifies standard nucleosynthesis calculations, since the neutrino asymmetry alters the initial balance of protons and neutrons, and it has been known for some time that matching the element abundances in the presence of a strong lepton asymmetry can require a higher baryon fraction than standard nucleosynthesis (see for instance Kang & Steigman 1992; Esposito et al. 2000, 2001; Kneller et al. 2001). The second is that it increases the radiation density in the Universe, by boosting the neutrino density beyond its usual value of 0.68 times the photon density.

At face value, these have highly desirable implications in cosmology for those favouring critical density on grounds of elegance, as was first pointed out by Adams & Sarkar (1998). First,

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if the preferred baryon density from nucleosynthesis could be significantly increased through the leptonic asymmetry, then the cluster baryon fraction would become a strong argument for critical density rather than against. Further, the extra radiation leads to a delay in matter–radiation equality, which shifts the characteristic bend in the matter power spectrum to larger scales mimicking the effect of the reduced matter density in the Λ CDM model. Finally, it was stressed (Lesgourgues & Peloso 2000; Esposito et al. 2001; Kneller et al. 2001) that a leptonic asymmetry could help in explaining microwave anisotropy results obtained last year from BOOMERANG (de Bernardis et al. 2000) and Maxima (Hanany et al. 2000), in which the observed weakness of the second acoustic peak favoured a high baryon fraction. Indeed, our initial studies for this present work indicated that critical-density models with leptonic asymmetry could fit not only these data, but also up-to-date constraints from large-scale structure, the cluster baryon fraction, and primordial element abundances. So, although unable to explain the supernovae data, this model could undermine much of the other evidence supporting the Λ CDM model.

This picture seems to be less promising after the publication of new microwave anisotropy results by the Degree Angular Scale Interferometer (DASI: Halverson et al. 2001; Pryke et al. 2001) and updated data analysis by BOOMERANG (Netterfield et al. 2001) and Maxima (Lee et al. 2001), which are incorporated into the results reported here. The new results contain no direct independent evidence for a cosmological constant, but within the framework of Λ CDM models exhibit excellent agreement with the baryon fraction from standard nucleosynthesis, while an excess of baryons is a key ingredient for the success of critical-density models. However, a high baryon fraction may yet be allowed in the presence of a leptonic asymmetry, and the true test of the idea lies in detailed comparison with observations, which is the purpose of our paper. We will see that the situation is not at all promising for the simplest case of massless neutrinos, which have trouble fitting many types of observation. However, there is now considerable experimental evidence that neutrinos actually possess a small mass, and the effects of this need to be included. The neutrino mass provides an additional modification to the matter power spectrum through neutrino free-streaming (as in the mixed dark matter scenario), and we find that this enables excellent fits to many observational data to be obtained. Unfortunately, because of the latest BOOMERANG results the model fails to explain the baryon fraction in clusters as well as the present acceleration.

2 THE LEPTON ASYMMETRY MODELS

The lepton asymmetry models are in most respects the same as conventional structure formation models, in particular relying on the presence of CDM, but add new parameters describing the magnitude of the lepton asymmetry and the mass of the neutrinos. In principle the masses at least are not extra parameters as compared to the standard cosmology, in that there is now substantial evidence that neutrinos do have mass; however in the presence of a lepton asymmetry the neutrinos may have a more significant impact on predictions for a given mass as the asymmetry increases their number density. To compensate for the addition of these extra parameters, we remove the cosmological constant.

Provided that neutrinos reach thermal equilibrium before decoupling, the leptonic asymmetry for each flavour species can be conveniently parametrized by the ratio of chemical potential to

temperature, $\xi_{\nu_i} = \mu_{\nu_i}/T_{\nu_i}$ (with $i \in \{e, \mu, \tau\}$). Neutrinos with a chemical potential are called degenerate neutrinos because the asymmetry enhances their total density. When the neutrinos are in the relativistic regime, this effect is strictly equivalent to a change in the effective number of standard neutrinos, in excess of the usual value of three, of

$$\Delta N_{\text{eff}} = \sum_i [30(\xi_{\nu_i}/\pi)^2/7 + 15(\xi_{\nu_i}/\pi)^4/7]. \quad (1)$$

All the generation mechanisms proposed so far predict different values of ξ_{ν_i} for each species, at least in the absence of fine tuning. This is a crucial point because the density of ν_e and $\nu_\mu + \nu_\tau$ have opposite effects on the neutron-to-proton ratio at freeze-out during BBN and on the production of light elements. More precisely, nucleosynthesis in the presence of a lepton asymmetry (known as degenerate BBN) requires three ingredients in order to be compatible with the observed abundances of deuterium, helium-4 and lithium-7 : (i) an increase¹ in ν_e density ($\xi_{\nu_e} > 0$); (ii) an increase in the baryon density; (iii) an increase in the total density of radiation (and expansion rate of the Universe), bigger than the one resulting from (i), and parametrized by an effective number of standard neutrino species $N_{\text{eff}} > 3$. There are many possibilities for enhancing the radiation density: the mu and/or tau neutrino may have a leptonic asymmetry bigger than that of the electronic neutrino,² or may become slightly non-relativistic during BBN (Hansen & Villante 2000), and apart from the three flavour neutrinos many scenarios predict that extra relativistic degrees of freedom could be present during nucleosynthesis (for instance, axions). Hannestad (2001) has recently studied limits on the number of neutrino species from the latest data (including models with a cosmological constant).

Standard BBN, which corresponds to $\xi_{\nu_i} = 0$, predicts a baryon fraction given by $\Omega_b h^2 = 0.019 \pm 0.002$, and an effective neutrino number close to three. In the following analysis we will focus on a baryon fraction in the range $0.015 < \Omega_b h^2 < 0.035$. In this case, according to the most recent studies of degenerate BBN (Esposito et al. 2000, 2001; Kneller et al. 2001), the ν_e asymmetry parameter should be in the range $0 < \xi_{\nu_e} < 0.5$, while the required effective neutrino number could be as big as 15 or even 20. Using equation (1) we see that the contribution of ξ_{ν_e} to ΔN_{eff} is negligible; therefore, when we study the spectrum of microwave anisotropies and large-scale structure, we can completely forget about ξ_{ν_e} , and consider the constraint from degenerate BBN to lie simply in the $(\Omega_b h^2, N_{\text{eff}})$ plane.

The calculations of matter and radiation power spectra were carried out using a modified version of the CMBFAST code (Seljak & Zaldarriaga 1996), as described in Lesgourgues & Pastor (1999).

3 OBSERVATIONAL CONSTRAINTS

For each model, we define a χ^2 statistic including the following terms: first, 19 data points from the new analysis of BOOMERANG (Netterfield et al. 2001), 13 from the new analysis of Maxima (Lee et al. 2001), and 9 from DASI (Halverson et al. 2001); secondly, 22 data points from the PSCz redshift survey

¹ Actually, there is also a small allowed region in parameter space with $\xi_{\nu_e} < 0$, reduced baryon density and $N_{\text{eff}} < 3$, but this is irrelevant in the present framework.

² i.e., $|\xi_{\nu_\mu} + \xi_{\nu_\tau}| > \xi_{\nu_e}$. However, successful implementations require only a factor of order 5 or so between $|\xi_{\nu_\mu} + \xi_{\nu_\tau}|$ and ξ_{ν_e} , which seems to be compatible with most mechanisms of large leptonic asymmetry generation.

(Hamilton & Tegmark 2000); and finally, a constraint on the matter spectrum normalization σ_8 from the number density of galaxy clusters. For the last, we adopt the rather conservative constraint $\sigma_8 = 0.56 \pm 0.056$ (1σ) from Viana & Liddle (1999). We also reran the analysis using the tighter limit $\sigma_8 = 0.495 \pm 0.034$ (1σ) recently obtained by Pierpaoli, Scott & White (2000), but this made no qualitative difference to our conclusions and so we do not report those results here.

For BOOMERANG and Maxima, we treat each data point as uncorrelated, with approximately Gaussian window functions. We take into account the fully correlated calibration error and the multipole-dependent beam plus pointing error, minimizing over the corresponding parameters. The likelihood function can be written as $\mathcal{L} = e^{-\chi^2/2}$ provided that the data points are almost Gaussian distributed. For Maxima we use the results for ΔT (table 1 in Lee et al. 2001) which have almost symmetric errors (except for the last two points which do not matter because these points provide mainly upper limits). The beam plus pointing uncertainty (calculated from the same table) turns out also to be symmetric for ΔT_l , so we can define a χ^2 for Maxima as

$$\chi^2 = \sum_l \frac{[\Delta T_l^{\text{theo}} - (1 + c\sigma_c + b\sigma_{b,l})\Delta T_l^{\text{obs}}]^2}{\sigma_l^2} + b^2 + c^2, \quad (2)$$

with a 1σ calibration uncertainty $\sigma_c = 0.04$, and a 1σ beam plus pointing uncertainty which is well fitted by the function $\sigma_{b,l} = 10^{-6}l^{1.7}$. For each model, we minimize the χ^2 over b and c . For BOOMERANG, we use a similar expression. However, in Netterfield et al. (2001), symmetric error bars are given for $D_l \equiv (\Delta T_l)^2 = l(l+1)C_l/2\pi$. Therefore, we define the χ^2 directly on this quantity with a 1σ calibration uncertainty $\sigma_c = 0.20$. The beam errors (read from fig. 2 in Netterfield et al. 2001) are symmetric for ΔT_l with $\sigma_{b,l} = 0.215 \times 10^{-6}l^2$ at 1σ . For simplicity, we assume a Gaussian beam error for D_l with twice the uncertainty.

For the DASI data, Pryke et al. (2001) indicate that the use of the exact window functions, and of a transformation that gives exactly Gaussian errors (Bond, Jaffe & Knox 2000), has only a modest impact on parameter extraction. On the other hand, the points cannot be treated as uncorrelated. Accordingly, we define the following covariance matrix

$$M_{ij} = \Delta D_i V_{ij} \Delta D_j + s^2 D_i D_j, \quad (3)$$

using the data points $D_l \pm \Delta D_l$ and the correlation matrix V_{ij} from Halverson et al. (2001, tables I and II). The fully correlated uncertainty s equals 0.08. The χ^2 is then defined as

$$\chi^2 = \sum_{i,j} (D_i^{\text{theo}} - D_i^{\text{obs}}) M_{ij}^{-1} (D_j^{\text{theo}} - D_j^{\text{obs}}). \quad (4)$$

We compute the total χ^2 values on a grid in parameter space, and perform a multidimensional cubic spline interpolation in order to find the minimum and the confidence limits on each parameter.³ The precision and efficiency of this method crucially depends on

³To marginalize over unwanted parameters, we maximize the likelihood function instead of integrating over these parameters (the two techniques would be strictly equivalent only for a multivariate Gaussian likelihood). Therefore, our confidence limit computation scheme is less rigorous than in current state-of-the-art analyses (Jaffe et al. 2001; Lange et al. 2001; Netterfield et al. 2001), but because of its simplicity it is widely used by many other authors, and gives a fairly good hint of the true error bars [see for instance the discussion in Tegmark & Zaldarriaga (2000) and Tegmark, Zaldarriaga & Hamilton (2001)].

the choice of a particular parameter basis. Our seven cosmological parameters are the overall normalization [automatically adjusted to match the COBE observations (Bennett et al. 1996; Bunn & White 1997) by the CMBFAST code that we use], the baryon fraction $\Omega_b h^2$, the scalar tilt n_s , the optical depth to reionization τ , the mass of the degenerate neutrino m_ν , the effective neutrino number N_{eff} (we recall that in the case of massive neutrinos, this number is defined at nucleosynthesis, not today), and a final parameter measuring the dark matter density. This last parameter could be taken as $\Omega_{\text{dm}} h^2$ (where $\Omega_{\text{dm}} = \Omega_{\text{cdm}} + \Omega_\nu$); however, this choice would lead to an exceedingly large computing time because there is a degeneracy between $\Omega_{\text{dm}} h^2$ and the neutrino parameters (m_ν, N_{eff}). In other words, for a given cosmological model and set of observations, the likelihood regions are elongated along a direction that can be found only empirically, and the χ^2 varies very slowly when the function $p_h(\Omega_{\text{dm}} h^2, N_{\text{eff}}, m_\nu)$ associated with the degeneracy is almost constant. The best time-saving strategy is to use p_h directly as the last free cosmological parameter. The preferred value of h (and of any other combination of the cosmological parameters) can then be recovered a posteriori. In most cases studied hereafter, we find that $p_h = \Omega_{\text{dm}} h^2 N_{\text{eff}}^{-1} (3.5 + m_\nu)^{-1}$ is a fairly good parametrization of the degeneracy in the vicinity of the minimum (with m_ν expressed in electron-volts).

In addition to the six free cosmological parameters, our model includes a free PSCz bias. The number of degrees of freedom is therefore $(19 + 13 + 9 + 22 + 1) - (6 + 1) = 57$. Actually, the constraints from PSCz on the largest scales are so loose that this number is somewhat overestimated.

3.1 The massless neutrino case

The results for the massless neutrinos are summarized by the individual parameter probability distributions, plotted in Fig. 1. The values for the best-fitting model and the 95 per cent confidence level are given in Table 1.

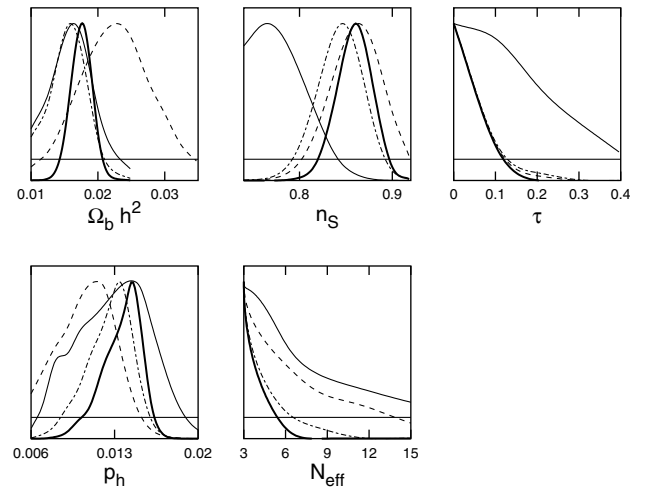


Figure 1. The probability distribution for each cosmological parameter, in the case of one massless degenerate neutrino. The thick solid lines show the result including all the data. Parameter values are allowed at the 95 per cent confidence level when the probability exceeds the horizontal line. The thin curves show the constraints obtained by combining just one CMB experiment with the other non-CMB data: solid is BOOMERANG, dashed is Maxima and dot-dashed is DASI. Although Maxima favours a significantly higher baryon fraction, and BOOMERANG a lower scalar tilt, the three data sets are found to be perfectly compatible.

Table 1. The preferred value and 95 per cent confidence limits for each cosmological parameter, in the case of one massless and one massive degenerate neutrino family. The upper part refers to the parameter basis used in the interpolation, with p_h defined as in the text. The lower part refers to useful combinations of these parameters, including the leptonic asymmetry parameter ξ_ν , the age of the Universe t_0 and the quantity $\Omega_b h^{1.5}$ which can be compared with the baryon fraction in galaxy clusters (the range given by Ettori & Fabian (1999) is 0.060 ± 0.025 at 2σ confidence level).

	Massless ν			Massive ν		
	min	best	max	min	best	max
$\Omega_b h^2$	0.014	0.018	0.021	0.016	0.020	0.025
n_s	0.82	0.86	0.90	0.90	0.96	1.02
τ	0	0	0.12	0	0.10	0.36
p_h	0.010	0.014	0.016	0.0066	0.0075	0.0089
N_{eff}	3	3	5.5	7	11	15
m_ν (eV)	—	—	—	0.60	0.85	1.5
b	1.05	1.2	1.35	1.2	1.4	1.5
h	0.38	0.41	0.47	0.54	0.60	0.71
$\Omega_{\text{cdm}} h^2$	0.13	0.15	0.17	0.22	0.29	0.42
$\Omega_\nu h^2$	—	—	—	0.03	0.06	0.08
ξ_ν	0	0	2.1	2.8	3.3	3.9
σ_8	0.57	0.65	0.73	0.45	0.54	0.63
t_0 (Gyr)	14	16	17	9	11	13
$\Omega_b h^{1.5}$	0.022	0.028	0.034	0.023	0.026	0.033

The results for this model are disappointing. The best-fitting model has a χ^2 of 61, which given the number of degrees of freedom looks satisfactory. However the properties of the best-fitting model are undesirable. The preferred values $\Omega_b h^2 = 0.018$ and $N_{\text{eff}} = 3$ match the standard BBN prediction, but this is not a good thing in the present context; since we do not obtain a high baryon density, we cannot explain the cluster baryon fraction. [Our predicted value for $\Omega_b h^{1.5}$ and the observed lower bound (Ettori & Fabian 1999) have no overlap at the 2σ level.] A further problematic aspect of this model is its low preferred value of h : this gives an impressively large age, but is in considerable discrepancy with direct h measurements. Finally, we must recall that we have made no attempt to obtain a presently accelerating universe.

We are therefore forced to conclude that the massless neutrino case has too many failings against observations to be considered a viable model.

3.2 The massive neutrino case

We now suppose that the neutrino family with the leptonic asymmetry⁴ has a mass m_ν . Now the degenerate neutrino can make up a significant fraction of the dark matter, as in the mixed dark

⁴ In the massless case our results were model-independent, since we did not privilege a particular scenario for the origin of the extra relativistic degrees of freedom. When taking into account a neutrino mass m_ν , we could distinguish various cases: first, the large chemical potential responsible for $N_{\text{eff}} > 3$ during BBN can belong to the massive neutrino family; alternatively, it can be shared between one species with negligible mass and one with arbitrary mass m_ν ; finally, the extra radiation density could be attributed to particles other than flavour neutrinos. For brevity, we only discuss the simplest case of a single massive degenerate neutrino family (ν_μ or ν_τ). Most other situations would give comparable results, but with a higher preferred value of the mass, since the neutrino free-streaming effect is enhanced by the leptonic asymmetry (Lesgourgues & Pastor 1999; Lesgourgues, Pastor & Prunet 2000).

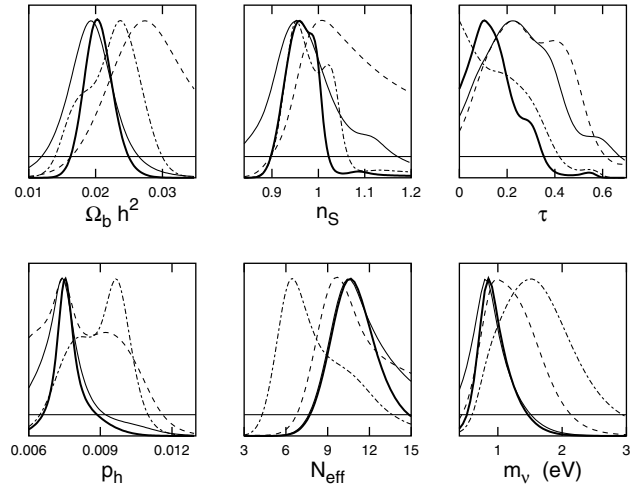


Figure 2. The probability distribution for each cosmological parameter, with one family of massive degenerate neutrinos. As in Fig. 1, the thick solid line shows the results from the complete data set, while the thin curves combine the non-CMB data with each of the three CMB experiments individually. Maxima and DASI allow a significantly higher baryon fraction than BOOMERANG, although the three data sets are compatible.

matter scenario, and its free-streaming while relativistic suppresses small-scale matter perturbations. With this additional free parameter, the minimum of χ^2 shows a large degeneracy along p_h : unreasonably large values of h are allowed, with a huge effective neutrino number maintaining the first acoustic peak and the power spectrum with the right shape and amplitude. This parameter region is uninteresting and should be removed. Indeed, $h > 0.58$ corresponds to a universe younger than $t_0 = 11$ Gyr, which is almost completely excluded. So, we must add to the χ^2 a ‘weak age prior’ $t_0 \geq 11$ Gyr.⁵ It is important to note that this prior almost does not affect the goodness-of-fit of the model, since the best-fitting model has t_0 close to 11 Gyr anyway.

The results for the massive case are also given in Table 1, and the probability for each individual parameter is shown in Fig. 2. The best-fitting model now has an impressively low χ^2 of 43 and some remarkable features. A large effective neutrino number between 7 and 15 is preferred, producing a high first acoustic peak as in Λ CDM models. This large lepton asymmetry is compatible with BBN up to $N_{\text{eff}} \approx 9$ as can be seen in Fig. 3. When it is combined with a mass close to 1 eV it gives the right shape and amplitude for the matter power spectrum. A neutrino mass smaller than 0.6 eV is excluded at more than 95 per cent confidence; this result is in good agreement with the oscillations reported at the Los Alamos Liquid Scintillation Neutrino Detector (SND: Athanassopoulos et al. 1998), which support evidence for a neutrino mass $m_\nu^2 \geq (0.1 - 1) \text{ eV}^2$.

Unfortunately, this positive picture is darkened by the predicted baryon density, which is as low as in the standard case: $\Omega_b h^2 = 0.020^{+0.005}_{-0.004}$ (95 per cent confidence). So, within the range of viable parameters the lepton asymmetry model can no longer reach the high baryon fraction potentially allowed by the degenerate BBN model. Studying the curves for individual CMB experiments in Fig. 2, we see that this result is primarily driven by the new

⁵ Technically, this is done by multiplying the likelihood function by a Gaussian cut-off, if and only if $t_0 \leq 11$ Gyr. The variance is chosen so that at $t_0 = 10$ Gyr the cut-off factor equals 1/2.

BOOMERANG results, with both DASI and Maxima still allowing significantly higher values; note in particular that the inclusion of a neutrino mass makes DASI compatible with a higher baryon fraction than in the massless case. With all data taken into account, the model is now restricted to $\Omega_b h^{1.5} \leq 0.033$, more than 2σ away from the Etti & Fabian (1999) cluster bound.

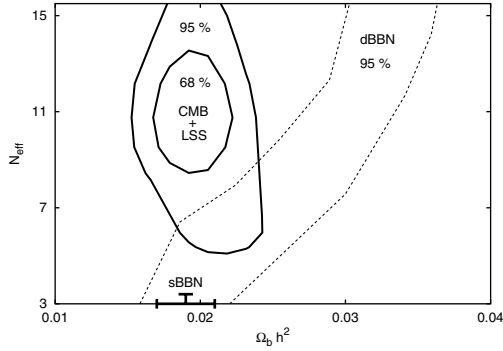


Figure 3. The thick lines show the allowed region in the $(\Omega_b h^2, N_{\text{eff}})$ parameter space, at 68 and 95 per cent confidence levels, for one family of massive degenerate neutrinos. On the lower axis we show the standard BBN prediction, and the thin curves show the region allowed at 95 per cent confidence level by degenerate BBN (Esposito et al. 2000, 2001). The regions overlap for $5 \leq N_{\text{eff}} \leq 9$.

4 SUMMARY

We have performed a detailed comparison of critical-density models including leptonic asymmetry with the latest CMB and LSS data, in order to investigate their viability as alternatives to the Λ CDM model. Some sample power spectra are shown in Fig. 4. We have found that very good fits to those data are available, as a result of the combined effect of the large lepton asymmetry (which is compatible with primordial abundances) and that of a neutrino mass ~ 1 eV (which is in good agreement with LSND). This model cannot hope to explain the supernovae data, but has the prospect of undermining the other support for the Λ CDM paradigm which has led to its wide acceptance. Unfortunately, the newest CMB data introduce a new problem for this model, which is that the baryon density is now constrained to be so low that fits to the cluster baryon fraction are not possible, which is disappointing as the lepton asymmetry model had the potential to allow higher baryon densities while remaining compatible with nucleosynthesis. The main driving force for this conclusion is the new analysis of the BOOMERANG data (Lee et al. 2001); the other new CMB data still permit a higher baryon density in the presence of a massive degenerate neutrino. Given the subtle effects of the neutrino degeneracy, and the various uncertainties in the new CMB data (calibrations, tilts), this was not obvious by eye, and it is the main result of this paper.

We stress that our study does not provide a model-independent bound on the leptonic asymmetry in the Universe, since it could in

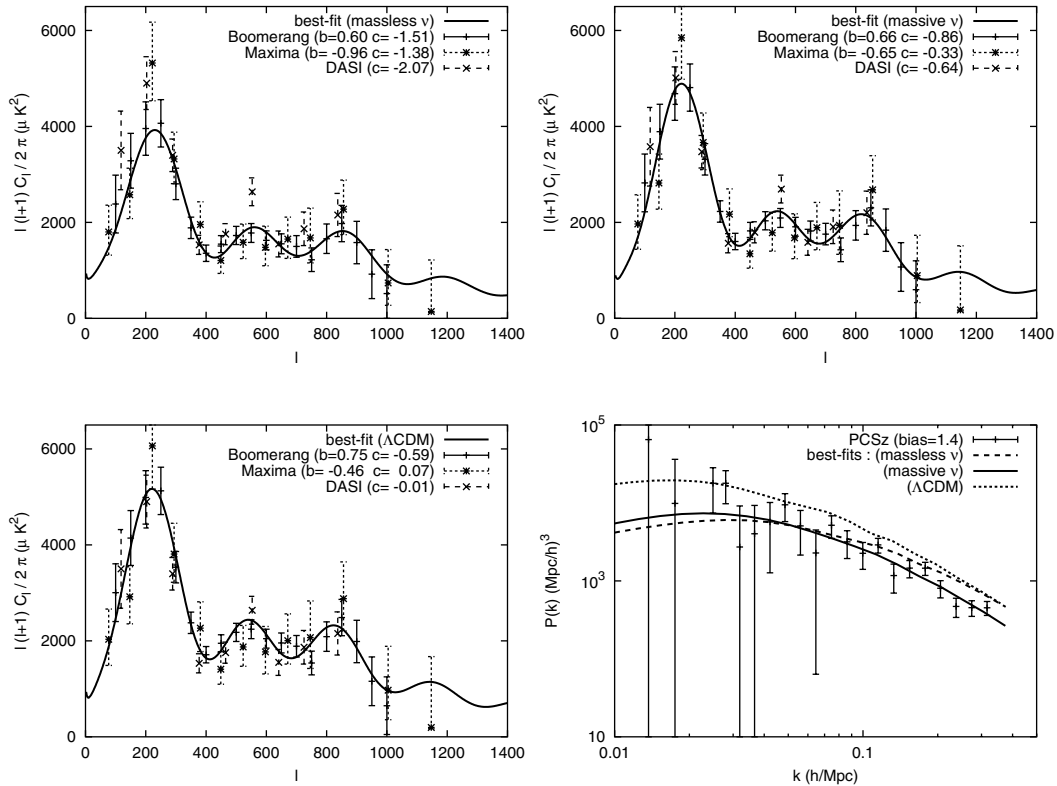


Figure 4. The CMB anisotropy and matter power spectra for three models – the massless and massive degenerate neutrino best-fitting models (whose parameters are given in Table 1), and the preferred Λ CDM model given by Wang, Tegmark & Zaldarriaga (2001): $\Omega_b h^2 = 0.020$, $\Omega_{\text{cdm}} h^2 = 0.012$, $\Omega_\Lambda = 0.66$, $n_s = 0.93$. The corresponding χ^2 (including CMB and LSS data) are equal to 61, 44 and 56 (the last is not very good simply because Wang et al. did not include a σ_8 constraint in their analysis). In the first three graphs, the BOOMERANG, DASI and Maxima data sets are shown with the appropriate beam and calibration errors (b, c) calculated for each case. The three matter power spectra are plotted together in the final plot, along with the PCSz points divided by the square of the bias factor $b = 1.4$ which minimizes the χ^2 for the massive neutrino model.

principle coexist with a cosmological constant. However, the lepton asymmetry is better motivated in the critical-density case, with it being used to remove the need for Λ . What our study shows is that following the recent results, the critical-density lepton asymmetry model experiences new observational difficulties which make it a less attractive proposition as a simple and elegant alternative to the Λ CDM cosmology.

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